$b \rightarrow s \ell \ell$ decays at Belle

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4 Search for Lepton Flavor Violating (LFV) decays $B^+ \to K^+ \ell\ell'$

5 Search for LFV decays $B^0 \to K^{*0} \ell\ell'$ [PRD 98.071101(R) (2018)]

6 Conclusion
Introduction

- $b \rightarrow s$ quark transition are FCNCs. These processes occur through penguin loop and box diagrams in SM.

These decays are highly suppressed and very small BR ($\mathcal{O} (10^{-6})$).

These decays are very sensitive to NP.

Probes NP models at energy scales higher than direct searches ($\sim 100$ TeV).

**New physics can contribute by:**

- enhancing or suppressing decay rates.
- modifying the angular distribution of the final state particles.
The amplitude of a hadron decay process is described as:

\[ A(M \to F) = \langle F | H_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) \langle F | O_i(\mu) | M \rangle \]

- **CKM couplings**
- **Wilson coefficients** \((\mu = \text{scale})\)
- **Hadronic Matrix Elements**

Wilson coefficients \(C_i\) = Perturbative short distance effects

Operators \(O_i\) = non-perturbative long distance effects.

\(i = 7\) : Photon penguin
\(i = 9, 10\) : Electroweak penguin

NP can affect SM operator contributions (Wilson coefficients) and/or enter through new operators.

Contribution of \(C_7, C_9\) and \(C_{10}\) depends on \(q^2\) (invariant mass square of two leptons).
Test of Lepton Flavor Universality (LFU) ($R_{K}^*$)

**LFU in $B^0 \to K^{*0} \ell^+\ell^-$**

- LHCb measurement of
  \[ R_{K^*} = \frac{BR(B^0 \to K^{*0} \mu^+\mu^-)}{BR(B^0 \to K^{*0} e^+e^-)} \]
  shows deviations from SM expectation.
  
  \[ R_{K^*}(0.045 < q^2 < 1.1 \text{ GeV}^2/c^4) = 0.66^{+0.11}_{-0.07} \pm 0.03 \]
  \[ R_{K^*}(1.1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.69^{+0.11}_{-0.07} \pm 0.05 \]

- Compatibility with the SM estimated to be at the level of 2.1 − 2.3σ for low $q^2$ and 2.4 − 2.5σ at central $q^2$ for a data sample of 3 fb$^{-1}$.

- Belle measurement for whole $q^2$ region, $R_{K^*} = 0.83\pm0.17\pm0.08$, is consistent with SM prediction.

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Test of LFU ($R_K$)

**LFU in $B^+ \rightarrow K^+ \ell^+ \ell^-$**

- Theoretically, similar to $B \rightarrow K^* \mu^+ \mu^-$, but $K$ is a scalar.
- These observables are theoretically very clean, as most of the hadronic uncertainties cancel out in the ratio.
- LHCb (PRL 113, 151601(2014)) shows deviation from SM

$$R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

in $q^2 = [1 - 6] \text{ GeV}^2/c^4$ : 2.6σ tension for 3fb$^{-1}$ data sample.
- The value of $R_K$ for Belle was consistent with unity within the uncertainty limit measured for a data sample of 605fb$^{-1}$.
- Currently, the study of $R_K$ with Belle full data sample (711fb$^{-1}$) is going on, I will present here the sensitivity.
The decay channels used are $B^+ \rightarrow K^+ \ell \ell$ and $B^0 \rightarrow K^0_S \ell \ell$, where, $\ell \ell = \mu\mu$ or $ee$.

$K^\pm$, $\mu^\pm$ and $e^\pm$ particles satisfying PID are selected from tracks near IP. $K^0_S$ are selected using $K^0_S$ displaced vertex properties and with a mass window of $0.487 < M_{K^0_S} < 0.508$ GeV/$c^2$.

The kinematic variables those differentiate signal from background are

$$M_{bc} = \sqrt{E_{beam}^2 - |p_B|^2}$$
$$\Delta E = E_B - E_{beam}$$

where, $E_{beam}$ refers to the beam energy, which is half the center of mass (CM) frame energy. $E_B$ and $p_B$ are energy and momentum of $B$ candidate.
Peaking Backgrounds: The peaking backgrounds from $B \rightarrow KJ/\psi(\ell\ell)$ and $B \rightarrow K\psi'(\ell\ell)$ are vetoed by applying $q^2$ cut;  
\[ 8.5 < q^2 < 10.2 \text{ GeV}^2/c^4 \text{ for } J/\psi \]
\[ 13 < q^2 < 14 \text{ GeV}^2/c^4 \text{ for } \psi(2S) \]

The other peaking from $B \rightarrow D^0(K\pi)\pi$ (pion assumed muon mass hypothesis) is removed by applying invariant mass cut $i.e.$, $1.85 < M_{K\pi} < 1.865 \text{ GeV}/c^2$.

A Neural Network (NN) is trained with some event shape (LR KSFW, $\cos\theta_B$, $\cos\theta_T$,..), vertex quality ($\Delta Z$, $\chi^2(K\ell\ell)$,..) and kinematic ($E_{vis}^{(ROE)}$, $E_{miss}$..) variables to suppress background from continuum and generic $B$-decays.

The NN output is translated to NN’ using  
\[ NN' = \log \frac{NN - NN_{min}}{NN_{max} - NN} \]

where, $NN_{min} = -0.6$ is the minimum NN cut applied. $NN_{max}$ is the maximum NN value and is obtained from signal MC.

The minimum cut reduces $\sim 75\%$ of backgrounds, with $\sim 95\%$ signal efficiency retention.

NN’ has similar distribution for different $q^2$ bins for signal as well as backgrounds $\rightarrow$ same PDF can be used for different $q^2$ regions.
$R_K$ sensitivity at Belle

- 3D fit is performed using $M_{bc}$, $\Delta E$ and NN'.
- PDF are modeled as:

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>generic B</th>
<th>Continuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$</td>
<td>Crystal Ball + Gaussian</td>
<td>Exponential Argus Gaussian</td>
<td>Chebychev polynomial Argus Gaussian</td>
</tr>
<tr>
<td>$M_{bc}$</td>
<td>Gaussian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NN'</td>
<td>Bifurcated Gaussian + Gaussian</td>
<td>Gaussian</td>
<td></td>
</tr>
</tbody>
</table>

- $R_K(J/\psi) = 1.00 \pm 0.01$ (data), value is found to consistent with unity within the uncertainty in MC as well as in data.
- $B \to KJ/\psi(\ell\ell)$ is used to calibrate signal PDF of $B \to K\ell\ell$.
- Off-resonance sample which is taken 60 MeV below $\Upsilon(4S)$ resonance, used to study continuum background and fix the PDFs shapes.
- The backgrounds PDFs parameters for generic $B$ decay are floated.
3D fit is performed using $M_{bc}$, $\Delta E$ and $NN'$. 

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<td>Continuum</td>
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$B \rightarrow KJ/\psi(\ell\ell)$ is used to calibrate signal PDF of $B \rightarrow K\ell\ell$.

Off-resonance sample which is taken 60 MeV below $\Upsilon(4S)$ resonance, used to study continuum background and fix the PDFs shapes.

The backgrounds PDFs parameters for generic $B$ decay are floated.

Signal region: $M_{bc} > 5.27$ GeV/$c^2$, $-0.05 < \Delta E < 0.05$ GeV and $NN' > 0.5$. 
The $R_K$ uncertainty of Belle for whole $q^2$ region was 0.19 (statistical), measured for a data sample of 605 fb$^{-1}$ [PRL 103, 171801(2009)].

Our current expected statistical uncertainty is 0.2 for a bin of $1 < q^2 < 6$ GeV$^2/c^4$ and 0.1 for whole $q^2$ region.

If we consider LHCb result as central value, then the violet box shows our estimated uncertainty.

The $R_K$ estimation for high $q^2$ region is in progress.
The deviation from SM expectation in $R_K$ and $R_{K^*}$ from LHCb result possibly show LFU violation.

LFV can come together with LFU violation (S. L. Glashow et.al PRL 114, 091801 (2015)).

Currently Belle has published LFV decays $B^0 \rightarrow K^{*0} \ell\ell'$, where $\ell = \mu, e$ [PRD 98.071101(2018)].

We are also studying LFV decays $B^+ \rightarrow K^+ \ell\ell'$, where $\ell = \mu, e$.

Applied same particle selection criteria as that of $R_K$ study.

The main sources of peaking backgrounds are removed by applying invariant mass cut on events, coming from $B \rightarrow KJ/\psi(\ell\ell)$ i.e., $3.06 < M_{\ell_1\ell_2}, M_{K\ell_2} < 3.12 \text{ GeV}/c^2$ and around $D^0$ mass region for $B \rightarrow D^0(\rightarrow K\pi)\pi$, i.e., $1.84 < M_{K\ell_2} < 1.86 \text{ GeV}/c^2$.

3D fit is performed using $M_{bc}$, $\Delta E$ and NN'.

$B \rightarrow KJ/\psi(\ell\ell)$ ($\ell\ell = \mu\mu$ and ee) behave as control sample for these LFV modes.

Fitting procedure is almost similar to $R_K$ study, but here we have merge background in a single component.
Search for LFV decays $B^+ \rightarrow K^+ \ell \ell'$

- The expected upper limit on BR with 90% CL is estimated by

$$\mathcal{B}(UL) = \frac{N_{sig}^{(UL)}}{N_{BB} \times \varepsilon}$$

where, $N_{sig}^{(UL)}$ is number of signal events in the upper limit, $\varepsilon$ is signal yield efficiency, $N_{BB}$ is number of $B\bar{B}$ pairs = $7.7 \times 10^8$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{sig}^{(UL)}$</th>
<th>$\mathcal{B}(UL)$ ($10^{-8}$)</th>
<th>PDG $B$ ($10^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ e^-$</td>
<td>29.3</td>
<td>4.4</td>
<td>2.0</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^- e^+$</td>
<td>30.0</td>
<td>4.9</td>
<td>2.1</td>
<td>&lt; 0.9</td>
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</tbody>
</table>

- Our estimated upper limit are an order of magnitude better than that of the PDG upper limits, which are from BaBar [PRD 73(2006)092001].

S. Choudhury (IIT Hyderabad)
Search for LFV decays $B^0 \rightarrow K^{*0} \ell \ell'$

- The modes studied are $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^- \mu^+$ [PRD 98.071101(R)(2018)].
- Strong contribution from continuum and generic B backgrounds.
- Trained two NN to suppress backgrounds.
- Good agreement between data and MC.
- No evidence of signal observed $\rightarrow$ upper limit is estimated.

### Upper limit at 90% CL.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{UL}}^{(UL)}$</th>
<th>$\mathcal{B}(UL)$ (10$^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^+ e^-$</td>
<td>8.8</td>
<td>$-1.5^{+4.7}_{-4.1}$</td>
<td>5.2</td>
<td>1.2</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^- e^+$</td>
<td>9.3</td>
<td>$0.4^{+6.8}_{-4.5}$</td>
<td>7.4</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^\pm e^\mp$</td>
<td>9.0</td>
<td>$-1.2^{+6.8}_{-6.2}$</td>
<td>8.0</td>
<td>1.8</td>
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Conclusion

- Several anomalies in B decays indicating lepton non-universal interactions.
- LFU tests are extremely clean probes for NP.
- Particular interest is in ratio testing LFU since they are not affected by hadronic uncertainties.
- Anomalies indicating LFU, in general we should also observe LFV processes.
- Belle searched LFV $B^0 \rightarrow K^{*0} \mu^\mp e^\mp$ and the most stringent limit is found.
- Belle will publish soon the result of $R_K$ and $R_{K^*}$ with full data sample, including LFV decay modes ($B^\pm \rightarrow K^\pm \mu^\pm e^\mp$).

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 605/711 fb$^{-1}$</th>
<th>Bellell 5 ab$^{-1}$</th>
<th>Bellell 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ ([1.0, 6.0] GeV$^2$)</td>
<td>–</td>
<td>11%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_K$ (&gt; 14.4 GeV$^2$)</td>
<td>–</td>
<td>12%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_{K^*}$ ([1.0 – 6.0] GeV$^2$)</td>
<td>–</td>
<td>10%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$R_{K^*}$ (&gt; 14.4 GeV$^2$)</td>
<td>–</td>
<td>9.2%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$R_K$ (whole $q^2$)</td>
<td>19%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$R_K$ ([1.0, 6.0] GeV$^2$)</td>
<td>22%</td>
<td>–</td>
<td>–</td>
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Thank you!